# An Experimental Study of Clogging Fault Diagnosis in Heat Exchangers Based on Vibration Signals

Jianfeng Huang[1,2], Guohua Chen[1], Lei Shu[2], Shihua Wang[2], Yu Zhang[3]

[1] Institute of Safety Science&Engineering, South China University of Technology, Guangzhou, China
Jianfeng.huang@lab.gdupt.edu.cn
Mmghchen@scut.edu.cn
[2] Guangdong Petrochemical Equipment Fault Diagnosis Key Laboratory, Guangdong University of Petrochemical Technology, Maoming, China
Lei.shu@ieee.org
Shihua.Wang@lab.gdupt.edu.cn
[3] School of Engineering, University of Lincoln, Lincoln, U.K.
Yzhang@lincoln.ac.uk

***Abstract*—**

**The water-circulating heat exchangers employed in petrochemical industrials have attracted great attentions in condition monitoring and fault diagnosis. In this paper, an approach based on vibration signals is proposed. By the proposed method, vibration signals are collected for different conditions through various high-precision wireless sensors mounted on the surface of the heat exchanger. Furthermore, by analyzing the characteristics of the vibration signals, a database of fault patterns is established, which therefore provides a scheme for conditional monitoring of the heat exchanger. An experimental platform is set up to evaluate the feasibility and effectiveness of the proposed approach, and support vector machine based on dimensionless parameters is developed for fault classification. The results have shown that the proposed method is efficient and has achieved a high accuracy for benchmarking vibration signals under both normal and faulty conditions.**

***Index Terms*—Vibration Signal, Heat Exchanger, Clogging Fault, Fault Diagnosis, Support Vector Machine**

## I. Introduction

HEAT exchanger is a common device used to transfer heat. In modern refineries, the cost of heat exchangers is around 40% of the total investment in a facility; the corresponding maintenance workload can be as high as 60% to 70% of the total maintenance workload. Therefore it is extremely important to make sure that heat exchangers operate safely and economically.

Instead of purified water, the cooling medium used in a heat exchanger is industrial-grade circulating water, which continues to evaporate and effloresce during use; thus its salt content constantly increases. Meanwhile, carbon dioxide in the water turns into its gaseous form and escapes from the cooling tower, leading to the continuous formation of calcium carbonate scales within the heat exchanger. Further, when the circulating water is exposed to the air, a large amount of dust as well as mud pellets and microorganisms dissolve into the water. Much of this material is then deposited on the inner walls of the heat exchangers tubes, forming scales. According to a survey by Steinhagen [1], of 3000 heat exchangers of different types used by 1100 companies in New Zealand, more than 90% showed varying degrees of scaling within their tubes.

Over time, scaling on the inner walls of the heat exchangers tubes will cause the fluid inside to change its direction of flow, thus generating a transverse force that causes the tubes to vibrate. If some of these tubes are heavily scaled or blockedłgiven that the velocity of fluid at the inlet is fixedłthe flow rate and pressure in the other tubes will be increased and the heat exchanger will vibrate violently. If this condition is not treated in a timely manner, leakage will ensue, leading to a significant financial cost. According to the statistical data, some 30% of heat exchangers break down because of vibration problems, indicating that the vibration of tube bundles is a major cause of damage [2]. This issue has become a key cause of concern in petrochemical industries; that is, it is considered vital to monitor, in a timely manner, the clogging conditions in heat exchangers during use so as to reduce the frequency of their maintenance and ensure the safe operation of these devices by analyzing their vibration signals.

Major facts discussed in this paper include the following:

- Starting with the problem of monitoring, the vibration mechanism of the water-circulating heat exchanger is described and the corresponding research reviewed. Finally a condition-monitoring approach based on the heat exchangers vibration signals is proposed.
- The following procedure is described: An experimental platform for a water-circulating heat exchanger was established and a support vector machine (SVM) used to classify the dimensionless parameters of its vibration signals. This procedure verified the divisibility of the vibration signals generated by the heat exchanger under both normal and fault conditions.

## II. Related Research

### A. Condition Monitoring of Heat Exchangers

The fault diagnosis of heat exchangers has posed a major challenge in the industry because faults such as leakage and clogging within the heat-exchange tubes are not visible. The fault-monitoring techniques used in todays refineries are relatively outdated [3]., the major methods being the monitoring of PH values, oil content, chemical oxygen demand, residual chlorine, the functioning of specific instruments and etc. For example, in the Maoming Ethylene Factory, the main fault-monitoring method used with its water-circulating heat exchanger is to determine the difference in temperature at the water inlet versus the water outlet. However, the accuracy of this method is influenced by many external factors. For instance, the temperature of the medium entering the exchanger may not be stable; it can fluctuate to some extent, and this will have a direct effect on the temperature difference.

However, by developing an online device to monitor the heat exchanger, sensors can be installed in different parts of it so as to monitor changes in the circulating water continuously, thus enabling online detection and identification. This method has achieved considerable success [4], with commercial products available for use in countries including the United States, Germany, and Japan [5]. As described in reference [6], a single-chip microcomputer (SPCE061A) was utilized to construct an online monitoring and controlling system designed to detect the temperature at the inlet and outlet as well as that of the water vapor; it can also measure the flow rate and control the flow of both water and vapor. Stojan Persin et al. [7] applied analytical fault detection techniques to do real-time fault diagnosis for an industrial-scale pilot heat exchanger.An online monitoring and prediction system is proposed in reference [8], which explores the way in which this device monitors and predicts a heat exchangers performance, resulting in improved production efficiency of each individual unit, lower costs of production and maintenance, as well as a higher level of safety during production. The on-line performance monitoring of a shell-and-tube type heat exchanger using steam and water has been developed on the basis of a theoretical model to monitor input and output process variables [9]. An adaptive observer is used to estimate the overall heat transfer coefficient and detect a performance degradation of the heat exchanger [10]. Fuzzy models based on clustering techniques are used to detect leaks in a complex heat exchanger [11]. SVM and relevance vector machine (RVM) have been widely used in the condition monitoring and fault diagnosis of machinery [12]. The particle swarm optimization algorithm is applied to estimate the parameters of a SVM which is used to predict faults in a heat exchanger [13]. The Dynamic Principal Component Analysis (DPCA) method and a set of Diagnostic Observers (DO) were designed to online detect and isolate faults related to sensor or actuators malfunctions in a shell and tube industrial heat exchanger [14][15]. Dejan Dragan et al. [16] presented a two-stage modeling procedure based on prior knowledge and recorded data to detect faults for a heat exchanger in an incineration unit. Ingimundardttir et al. [17] presented a method for the detection of fouling in a cross-flow heat exchanger using wavelets.Paper [18] proposes a new method for fouling detection in a heat exchanger. It is based on the modeling of the system in a fuzzy TakagiC-Sugeno representation. With this representation, the design of a fuzzy observer with unknown inputs of polynomial types is obtained via a LMI formulation. Shu et al. [19][20] report a fault-diagnosis method in petrochemical water-circulating heat exchangers based on vibration and sound. Preliminary results show that it was difficult to identify faults by sound and that further research is required concerning vibration signals.

From these reports it is clear that several researchers have studied the online monitoring and fault-diagnosis system of water-circulating heat exchangers; however, these investigations are limited to the monitoring of parameters such as temperature, pressure, and flow rate, with little progress in the fault diagnosis of heat exchangers. Besides, since a heat exchanger is a static device and vibrations generated by the circulating water within the tubes is far less than that generated by mechanical rotation, little research has focused on condition monitoring utilizing vibration or sound parameters.

### B. Research on Vibrations in Heat Exchangers

The movement of fluid in a heat exchanger is very complicated, including cross flow, axial flow, and bypass flow in tube bundles; moreover, there are stagnant areas at the inlets and outlets of the tube bundles. The rate and direction of flow of various fluids continue to change irregularly, creating a heterogeneous force field for the heat transfer tube. Then the heat-transfer tube vibrates under the influences of several forces initiated by the flowing fluid. When the frequency of induced vibration comes close to the machines inherent frequency, the heat exchanger will vibrate violently, causing damage to the baffles and the joint between the tube and baffle. Further, the resonant vibrations of tube bundles, pumps, and compressors; the direct pulsating impact generated by rotating machinery; and the frequent on-off switching of the heat exchanger all induce the tube bundles to vibrate, finally causing them to fail.

Investigations of vibration conditions in heat exchangers have been conducted by several research groups. Feng et al. [21] utilized Fluent software to simulate the characteristics of flow-induced vibrations in a singe straight tube, two parallel tubes, two tandem tubes, and tube bundles, obtaining corresponding dynamic responses and characteristics of the flow field. Con-sidering aspects of modal shape and dynamic responses, Zheng et al. [22] analyzed the influence of vibrations induced by pulsating flow on the vibrations of heat exchangers. Wang et al. [23] studied the inherent vibration characteristics of planar elastic tube bundles and vibration patterns of the same elastic tube bundles under the influence of pulsating flow. They used Fluent software to achieve a simulated calculation of the pulsating flow generator; as a result, a vibration frequency in agreement with the real frequency was obtained. Chen et al. [24] fulfilled equivalent simulation analyses of vibrations in a heat exchanger using Ansys software and studied various factors that caused vibration of tube bundles. According to them, vibration of the tube bundles can be effectively avoided if the excitation frequency is kept away from the inherent frequency. Nevertheless, all this research was carried out based on the inherent vibration characteristics of the heat exchanger without any analysis of vibration conditions with regard to fault diagnosis.

In the present paper, the flow rate of the fluid is considered to be the direct factor that causes the tube bundles in a shell-and-tube heat exchanger to vibrate. When fluid runs through the tube and the Reynolds number reaches a certain value, asymmetrical alternately shed vortex wavesłnamely Karmans vortex streetsłappear periodically on both sides and the back of tubes. In the past couple of decades, studies of flow-induced vibrations have made significant progress in other countries and a highly accepted mechanism of flow-induced vibration has been proposed, e.g., vortex shedding and turbulent buffeting. The alternate formation and shedding of vortex generates a periodic exciting force perpendicular to the direction of fluid flow on both sides of tubes and causes the tubes to vibrate.

Theoretically, different vibration signals will be generated at distinct flow rates and under varying fault conditions in a heat exchanger, thus laying the foundation for this research.

## III. Proposed Methodology

### A. Signal-Acquisition Device

Signal acquisition is the prerequisite for collecting useful information and implementng condition monitoring and fault diagnosis. On the production sites of petrochemical companiesłowing to factors such as safely requirements, limited space, and cost of cablingłit is common for condition monitoring to be applied only to extremely important devices. With advantages such as flexible construction of a network and no necessity for cabling, the wireless sensor network has been an effective addition to the traditional wired monitoring network. In the study described here, wireless vibration sensor A104 and wireless access point BS903 (Beijing BeeTech Inc.) were used. Network construction was controlled by software, and nodes could be extended flexibly, which made it possible to install more measuring points in limited space and thus to collect vibration signals. Major features of the resulting setup are outlined below:

- Wireless vibration sensors were equipped with strong magnetic bases that could be directly mounted on the surface of a heat exchanger; therefore, any number of sensors could be installed anywhere in the heat exchanger following the requirements of measurement.
- One wireless access point could be connected to various wireless vibration sensors. Here a wireless access point adopted a wireless ratio frequency of 2.4 G, supported a visible distance of 100 meters, and provided a data transfer rate up to 250 kilobytes per second in air. It was directly connected to the computer software via a USB port.
- Considering that it is water flow impacting the baffles and walls of its tubes that mainly causes the vibrations of a heat exchanger, the vibrational acceleration should be very small. Therefore it was important that acceleration sensors should be able to detect vibration signals of very low amplitude. The A104 wireless acceleration sensor used in this researchłwhich has a maximum sampling frequency of 4000 Hz, a frequency response up to 500 Hz, and a measuring accuracy of 0.1 mgłfulfills this requirement.

### B. Analytical Method of Signals

Owing to the lack of a theoretical basis for analyzing the vibration signals of water-circulating heat exchangers, it is difficult to determine the exact vibration parameters to which the fault characteristics of the device are sensitive. As a consequence, based on the conventional analytical methods of vibration signals, the most common parameters in the statistical time-domain analysis of vibration signals (e.g., mean, variance, effective value, peak value, kurtosis, kurtosis factor, skewness factor, crest factor, impulse factor, margin index and shape factor) are analyzed. Instead of applying various signal processing and exchanging processes, these factors are used directly in the real-time detection of vibration signals, thus avoiding the occurrence of signal torture and leakage [25].

By using this feature to its full potential, the fault characteristic extraction of a water-circulating heat exchanger can be realized by choosing proper parameters, thus providing the basis for online monitoring. In addition, this method analyzes the frequency-domain responses of vibration signals and their frequency variance.

### C. Classification of Faults Based on a Support Vector Machine

SVM, a machine learning method proposed by Vapnik et al. [26]. The main ideas of SVM are shown in Figure 1. Circles represent the first samples and squares represent the second samples. $\mathrm{H}_0$ stands for the classification line. $\mathrm{H}_1$ and $\mathrm{H}_2$ are parallel to $\mathrm{H}_0$ and go through the samples which are closest to $\mathrm{H}_0$. The gap between $\mathrm{H}_1$ and $\mathrm{H}_2$ is named classification margin. Two types of samples can be divided by classification line $\mathrm{H}_0$ exactly. The optimal classification line represents the maximal classification margin. The plane equation is represented as following:

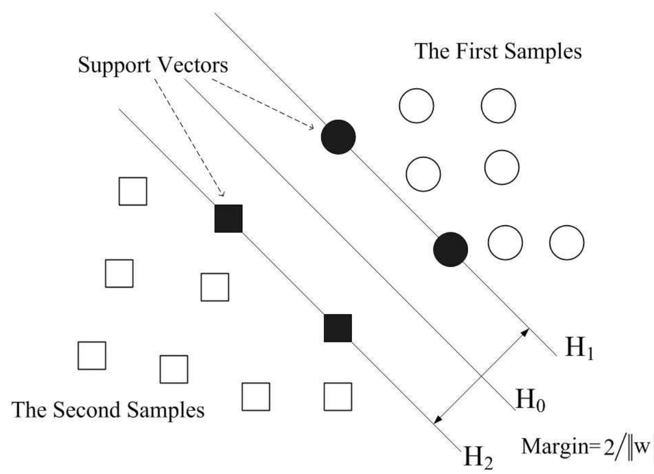


Fig. 1: Optimal hyperplane under linear separable condition

$$\omega \times x + b = 0 \tag{1}$$

It will get a linear separable sample set after the formula(1) normalized, $(\mathrm{x_i}, \mathrm{y_i}), (\mathrm{i} = 1, 2, ..., \mathrm{n}), \mathrm{x} \in \mathrm{R^d}, \mathrm{y} \in \{1, -1\}$. It meets the following classification definition:

$$y_i(\omega \times x + b) \geq 1(i = 1, 2, ..., n) \tag{2}$$

The current classification margin is $2/\|\omega\|$. The maximal classification margin equals to the minimum $\|\omega^2\|$. When it satisfies formula (2) and minimizes $\|\omega^2\|/2$, the optimal classification line appears. This moment, the training samples on $H_1$ and $H_2$ are support vectors.

SVM has greater generalizability than a neural network and solves small learning and classification problems more effectively. With limited information on characteristics, it reveals classification knowledge hiding behind the sampling data to its full capacity and solves problems of local extremum and the curse of dimensionality that are inevitable in neural network methods, demonstrating great practical value in the diagnosis of mechanical faults.

To evaluate the working condition of a water-circulating heat exchanger via vibration signals, it is essential to be able to distinguish between signals of normal and fault conditions. This diagnostic principle is shown in Figure 2, where various wireless sensors are installed in a water-circulating heat exchanger to form a wireless sensor network that can collect vibration signals from the heat exchanger under different conditions and obtain five dimensionless parameters: kurtosis factor, skewness factor, crest factor, impulse factor, margin factor, and shape factor. For each signal collected by a sensor, its fault eigenvalues are analyzed and then trained by an SVM, leading to the establishment of a fault classifier. By using this classifier, the condition of a signal can be determined.

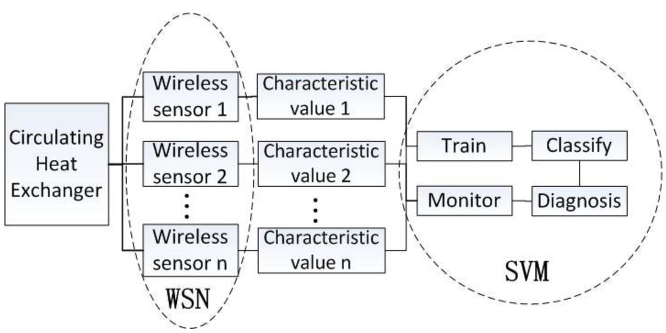


Fig. 2: The Model of SVM

## IV. Experimental Verification

To evaluate the effectiveness of vibration signals in monitoring the condition of water-circulating heat exchangers, an experimental model of a heat exchanger is set up, as shown in Figure 3.

This model has a similar structure and function to that of an industrial shell-and-tube heat exchanger, enabling heat exchange between a high-temperature and low-temperature fluids to be realized. To reduce the number of influencing factors, the experiments reported here discuss only the flow of water through the tubes but not the shell. The following major questions are considered:

- Are vibration signals generated by a water-circulating heat exchanger the same under normal and clogging conditions? This is a key point in the fault diagnosis of heat exchangers.

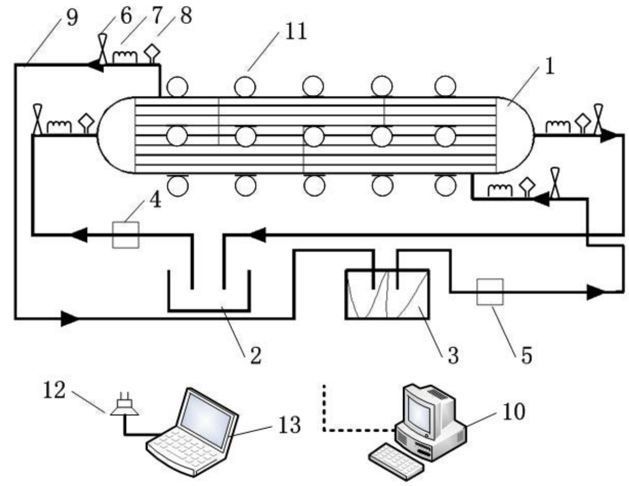


Fig. 3: Schematic drawing of a water-circulating heat exchanger.It mainly consists of (1) a heat exchanger, (2) a cooling-water tank, (3) a hot-water tank, (4) a cooling-water pump, (5) a hot-water pump, 6) flowmeters, (7) temperature sensors, (8) pressure gauges of tube pressure, (9) tubes, (10) a central control system, (11) wireless vibration sensors, (12) a wireless access point, and (13) a laptop computer with a data collection system.

- What are the major factors that influence vibration signals in a water-circulating heat exchanger? Do these factors (i.e., water flow rate and number of clogged tubes) obey a rule?
- Circulating water used in this experimental system is mainly driven by centrifugal pumps, and vibrations generated by these pumps are delivered to the heat exchanger through connecting tubes. The question is whether this fact influences the collection and processing of signals.

### A. Setup of the Experimental Platform

According to the model, an experimental platform is set up, as shown in Figure 4. Fluid inside the water-circulating heat exchanger flows through the tubes and shell, respectively, and, driven by centrifugal pumps, completes its course by running in and out of the heat exchanger. Parameter settings of the entire model of the water-circulating heat exchanger are monitored by the central control system, so that factors such as flux, temperature, and pressure can be adjusted according to different conditions. In total, there are 29 tubes in the tube bundles inside this heat exchanger, and by manually removing and inserting plugs, fault conditions with different numbers of clogged tubes can be simulated. Each condition (including the one without clogging) comes with the same inlet velocity and inlet temperature so that the factors influencing vibrations in a heat exchanger can be better studied. Wireless vibration sensors, with their strong magnetic bases, are mounted on the surface of the heat exchangers shell. These sensors collect vibration signals from the all the surfaces of the heat exchanger simultaneously. Then, by the signal analysis system, signal characteristics can be extracted.

### B. Condition Monitoring of the Heat Exchanger

From previous descriptions of vibration principles in a heat exchanger, it is known that the vibrations of a heat exchanger are caused mainly by fluid. However, the influence of fluid temperature on vibrations of the tubes is so trivial that this factor can be neglected; therefore this study focuses on the number of clogged tubes and flow rates as they influence the heat exchangers surface vibrations. In Figure 4, six wireless high-precision acceleration sensors on the exterior surface of a heat exchanger form a wireless sensor network that collects vibration signals from six different locations. Their current sampling frequency is 500 Hz, and following major conditions are monitored:

- Centrifugal pumps are closed, the heat exchanger is only supplied with tap water, and the velocity at the inlet of the heat exchanger is 0.6 L/s. Vibration signals both under the normal condition and with six tubes being clogged are detected, with results shown in Figures 5 and 6.
- Vibration signals under different clogging conditions are measured. By inserting plugs manually, the inner tubes of the heat exchanger are randomly clogged, the clogging number ranging from 0 (the normal condition) to 15. Each time one more tube is clogged, the corresponding vibration data are collected (the velocity at the inlet of the heat exchanger is the same as in step 1.
- Under the condition of six tubes being clogged, the velocity of water at the inlet of the heat exchanger increases from 0.5 to 1.6 L/s, with an increasing step of 0.1 L/s each time. Again the corresponding vibration signals are collected.

### C. Processing and Analysis of Signals

*1) Analysis of the influence of centrifugal pumps:* First, centrifugal pumps are shut down and the differences in vibration signals under normal and clogging conditions are studies in a water-circulating heat exchanger supplied with tap water.

Without the running of centrifugal pumps, Figure 5 shows two sets of vibration signals under normal conditions and the condition with six tubes being clogged; the inlet velocity of water is 0.6 L/s (tap water is supplied here). From the time-domain chart, the vibration amplitude obtained under the clogging condition is much greater than that obtained under normal condition. The frequency-domain chart shows several complicated frequencies of vibration signals under the normal condition, whereas there is only one fault-characteristic frequency (50 Hz) under the clogging condition, indicating a huge difference in these two cases.

The circulation of water in a heat exchanger is driven by centrifugal pumps. When the fluid velocity is set to 0.6 L/s under the influence of these pumps, vibration signals collected under the normal and clogging conditions are shown in Figure 6. From the time-domain chart, vibration amplitude under the clogging condition is significantly greater than that under the normal condition. Although the frequency-domain chart shows both the base frequency and multifrequency, the fault characteristic frequency (50 Hz) is the same as the that obtained without centrifugal pumps.

TABLE I: The characteristic values when six tubes are clogged

| Flow rate (L/S) | Mean absolute ($10^{-3}$g) | Root-mean -square ($10^{-3}$g) | fault-characteristic frequencies (Hz) |
|---|---|---|---|
| 0.6 | 1.798 | 1.565 | 50 |
| 0.8 | 1.498 | 1.305 | 43 |
| 1.0 | 3.254 | 2.785 | 32 |
| 1.2 | 3.561 | 3.050 | 50 |
| 1.4 | 5.713 | 4.901 | 55 |
| 1.6 | 11.84 | 10.09 | 50 |

By comparing Figures 5 and 6, it can be seen that vibrations generated by centrifugal pumps have a huge effect on the vibration of a heat exchanger. On the one hand, vibrations of the pumps enlarge the vibration amplitude of the heat exchanger; on the other hand, the regular vibrations of the centrifugal pumps are blended into vibration signals of the heat exchanger, and the regular vibration patterns of the centrifugal pumps are highlighted in both the time-domain and frequency-domain charts.

These results show that it is possible to differentiate the vibration signals of a water-circulating heat exchanger under normal condition and clogging conditions.

*2) Number of clogged tubes and fluid flow:* Firstly, the most common statistical parameters are used to analyze the vibration signals in a heat exchanger. Figure 7 shows the time-domain and frequency-domain charts of vibration signals generated by a heat exchanger at different flow rates when six tubes are blocked. From the time-domain chart, it can be seen that the amplitudes of vibration signals of a heat exchanger vary at different flow rates. Figure 8 and Table 1 show characteristic statistics of vibration signals generated by a heat exchanger, such as mean absolute value and root-mean-square value, all of which increase with the increase in flow rate.

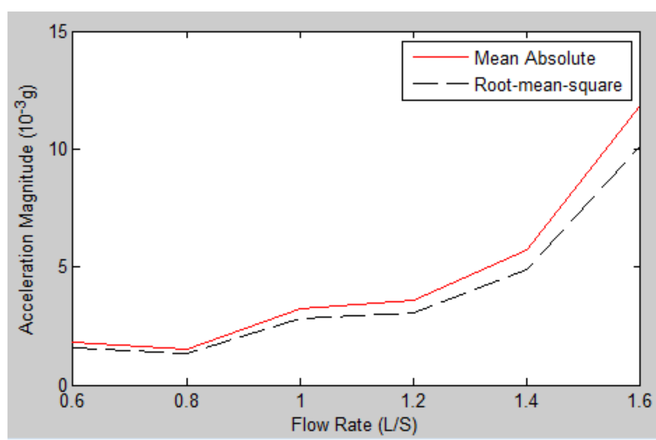


Fig. 8: The mean and root-mean-square value of flow rates when six tubes are clogged.

The violent vibration generated by working centrifugal pumps directly influences the wireless vibration sensors mounted on the surface of a heat exchanger. The frequency-domain chart shows the base frequencies and multifrequencies of the pumps. The base frequency of vibration signals generated by the centrifugal pumps can be calculated after measuring the rotation speed, and the base frequency and

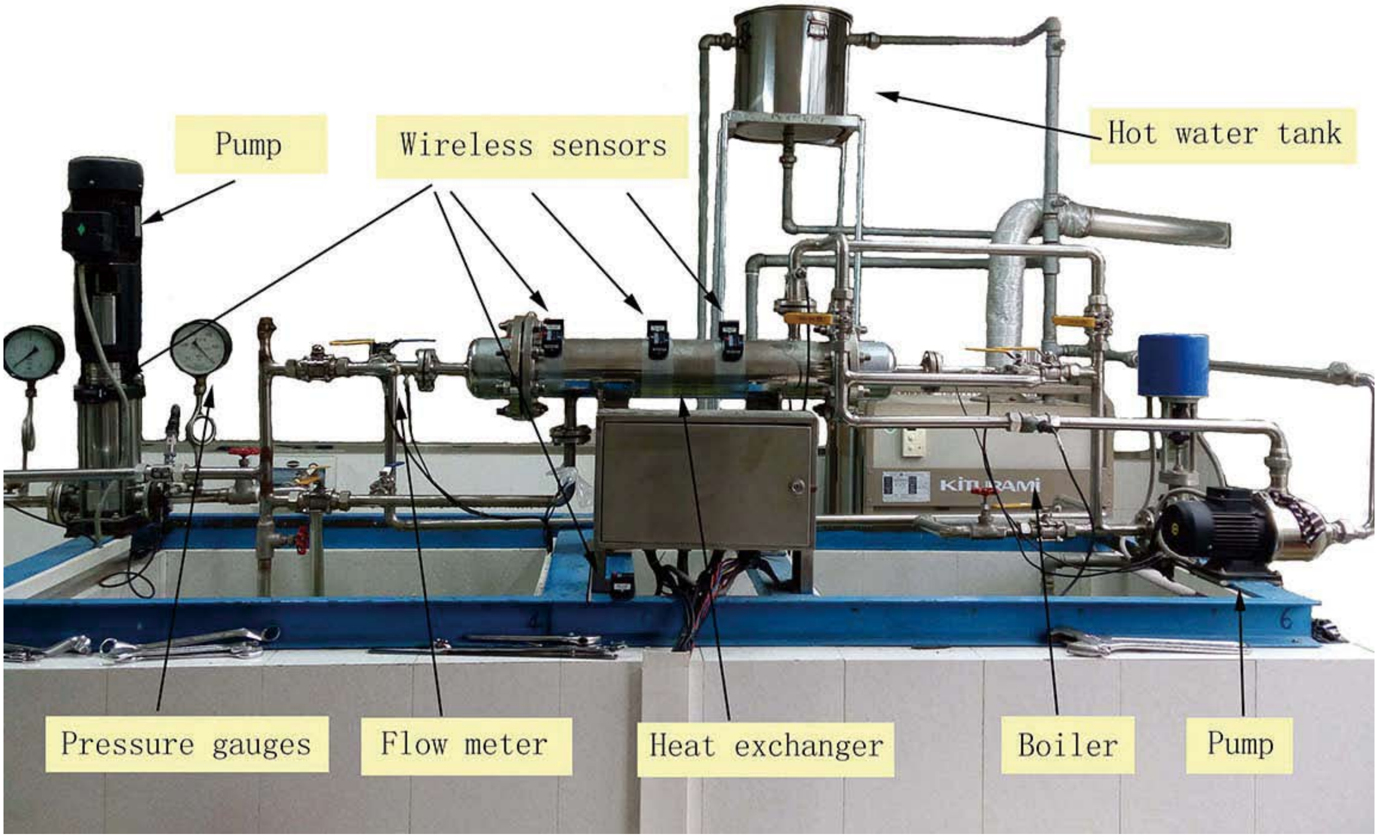


Fig. 4: The experimental platform of water-circulating heat exchanger.

multifrequencies of the centrifugal pumps can be determined from the frequency-domain chart. For instance, the values marked in Figure 7 are base frequencies and multifrequencies of the centrifugal pumps at different flow rates. Therefore, after subtracting the frequency of the centrifugal pumps, the characteristic frequency of clogging fault of a water-circulating heat exchanger can be obtained, as shown in Table 1.

In short, from the time-domain and frequency-domain analysis of the vibration signals from a heat exchanger, it is feasible to conduct fault monitoring and diagnosis by using vibration signals. And a fault characteristics database of the heat exchanger can be established by using vibration amplitude, base and multifrequencies of the centrifugal pumps, and fault-characteristic frequencies.

*3) SVM analysis based on dimensionless parameters:* Based on the previously described SVM model, normal and clogging conditions in a water-circulating heat exchanger are studied in terms of flow rates and clogging conditions.

- When the clogging condition is kept the same, the SVM model is used to study the differentiation of data between the one collected from the clogging condition and that from normal condition at different flow rates. Given the condition that six tubes are clogged and different flow rates are applied, a set of dimensionless parameters are calculated every 8000 data points, and 55 sets of parameters are obtained for the normal condition and the fault condition, respectively. For each flow rate, the normal data and data collected from the fault condition form a sample set of 55  2, from which, 50% of the sample set is randomly selected to train the SVM model while the rest is used for test. Further, every sample set collected at a different flow rate is considered a SVM training and test. Results are shown in Figure 9, where the accuracy is over 90%. After various experiments on different flowing rates, it is confirmed that clogging conditions can be differentiated from the normal condition.
- When the flow rate is fixed, the SVM model is adopted to study the differentiation of data collected from clogging and normal conditions. Each time a new clogging condition existsłthat is,when an additional tube is cloggedłnew data are collected, and there are 15 clogging conditions in total. Given a flow rate of 0.6 L/S, dimensionless parameters are calculated every 8000 data points, and a total of 55  15 data sets are collected for all the

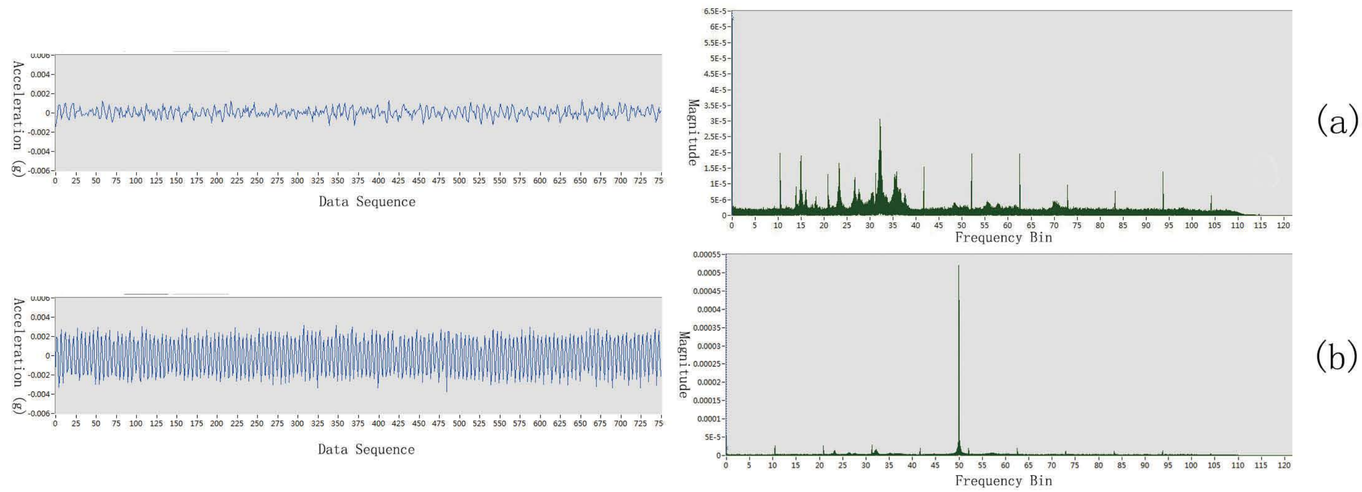


Fig. 5: Signal and spectrum of (a) 0 pipelines clogging and (b) 6 pipelines clogging with no pumps at 0.6L/S.

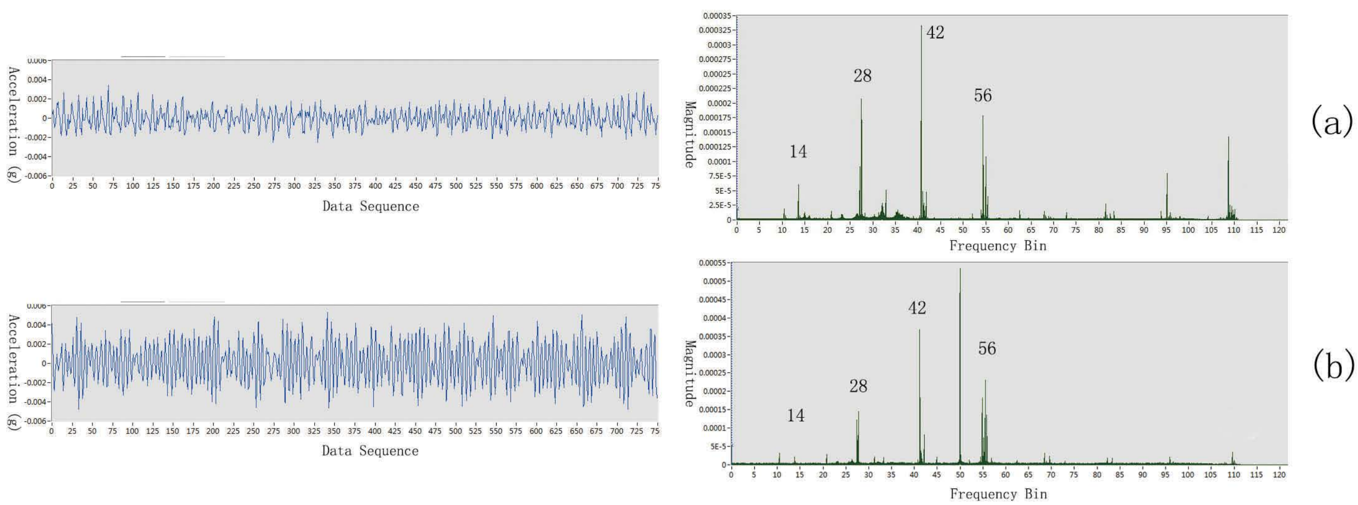


Fig. 6: Signal and spectrum of (a) 0 pipelines clogging and (b) 6 pipelines clogging with one pump at 0.6L/S.

clogging conditions. Later, 55 sets of data collected from the normal condition and another 55 sets of data collected from a certain clogging condition form a sample set of 110. Randomly, 50% of the sample set is selected for SVM model training, while the remaining 50% are used for test. For each clogging condition, the corresponding sample set is used for an SVM training and test; the results are shown in Figure 10, where the accuracy is greater than than 85%. After various experiments, it can be concluded that when the flow rate is fixed, clogging conditions of a water-circulating heat exchanger can be differentiated from the normal condition.

*4) Experimental analysis:* On the basis of a series of experiments using a model of a water-circulating heat exchanger, the clogging of tubes and flow rates were found to be key factors influencing the resulting vibration signals. Either by changing the number of clogged tubes or adjusting the velocities at the heat exchangers inlet, vibration signals can be modified. According to the principles of flow-induced vibration, when

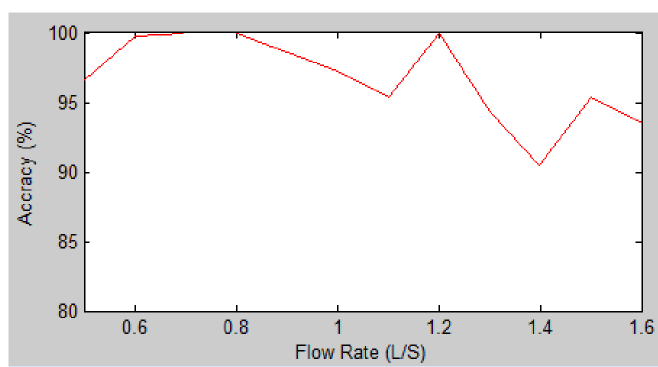


Fig. 9: The accuracy of fault detection at different flow rates when six tube are clogged.

the tube bundles of a heat exchanger are clogged to different degrees, the fluids flow rate and direction will also change. Given a certain flow rate at the inlet, if some tubes in a heat exchangers are clogged, the flow rate in the other tubes will

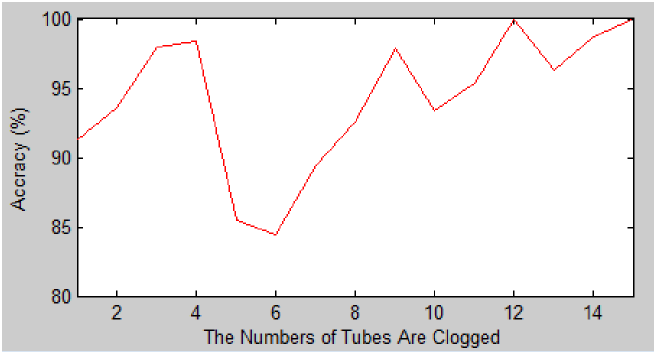


Fig. 10: The accuracy of fault detection when different numbers of tubes are clogged (the flow rate is 0.6 L/S).

increase, generating a periodic variation in the fluids impact on the inner walls of the tubes. This leads to a change in the vibration signals generated by the exchanger. From these systematic experiments, it can be concluded that:

- When the centrifugal pump is shut down, time-domain and frequency-domain charts of vibration signals generated by a heat exchanger are significantly different under normal and fault conditions. The accuracy of classification by an SVM is greater than 99.9%, demonstrating the feasibility of differentiating these two kinds of vibration signals.
- Vibrations generated by working centrifugal pumps influence the vibrations of the heat exchanger. The fault characteristic frequency of a heat exchanger can be determined under this condition by filtering the wave.
- The number of clogged tubes and velocities at the inlet of a water-circulating heat ex-changer are major factors that influence the resulting vibration signals. In using the SVM model to differentiate the normal and fault signals of the heat exchanger, an accuracy over 85% is achieved. Therefore the use of vibration signals to monitor clogging faults in heat exchangers is a relatively effective method.

## V. Conclusion

A condition-monitoring and fault-diagnosis method based on wireless vibration sensors in water-circulating heat exchangers has been proposed. By establishing an experimental platform for a water-circulating heat exchanger and performing a series of experiments that simulate clogging faults, it has become clear that vibration signals generated by a heat exchanger under normal and clogging conditions are significantly different. Based on dimensionless parameters in an SVM classification model, it is clear that the difference between vibration signals collected under normal conditions versus those collected under fault conditions is greater than 85%.

Therefore it is feasible to set up a condition monitoring system for a water-circulating heat exchanger based on vibration signals. However, although this SVM model provides relatively high accuracy in identifying whether the heat exchanger is clogged, further research is required to improve its diagnostic efficiency and accuracy (e.g., with regard to the exact number of clogged tubes). In the future, an improved multilevel fault-classification device can be designed based on the number of clogged tubes, thus providing better monitoring.

## VI. Acknowledgement

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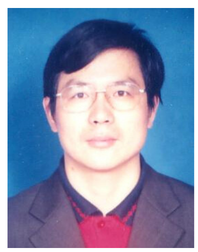
**Jianfeng Huang** is currently working toward the PhD degree at Institute of Safety Science & Engineering, South China University of Technology, Guangzhou, China. He received master degree from Guangdong University of Technology, Guangzhou, China, in 2006. From August 2006, he started to work in Guangdong University of Petrochemical Technology. He is currently an associate professor and the department head of safety engineering. From May 2013, he joined Guangdong Petrochemical Equipment Fault Diagnosis Key Laboratory. His research interests include: industrial wireless sensor networks, petrochemical equipment fault diagnosis and safety assessment.



**Guohua Chen** received Ph.D. degree of process safety from Nanjing Tech University, China. He is the councillor of China Occupational Safety and Health Association.He is currently a professor and department head of Institute of Safety Science & Engineering, South China University of Technology, Guangzhou, China. His research interests include safety, reliability, and risk assessment technology about process equipment.

**Lei Shu** received Ph.D. degree from National University of Ireland, Galway, Ireland, in 2010. Until March 2012, he was a Specially Assigned Researcher in a Department of Multimedia Engineering, Graduate School of Information Science and Technology, Osaka University, Japan. He is a member of IEEE, IEEE ComSoc, EAI and ACM. Since October 2012, he joined Guangdong University of Petrochemical Technology, China as a full professor. He is the founder of Industrial Security and WSNs Lab. He is serving as Editor in Chief for EAI Endorsed Transactions on Industrial Networks and Intelligent Systems, and associate editors for a number of famous international journals. He served as more than 50 various Co-Chair for international conferences/workshops. His research interests include: WSNs, Multimedia Communication, Middleware, Security, and Fault Diagnosis.

**Shihua Wang** received Ph.D. Degree of management science and engineer from China University of Technology, China. He is the lecturer of Guangdong University of Petrochemical Technology, China. His research interests include machine learning and petrochemical equipment fault diagnosis.

**Yu Zhang** received Ph.D. degree from Department of Civil Engineering, University of Nottingham, Nottingham, U.K., in 2011. She is currently a Senior Lecturer in the School of Engineering, University of Lincoln, Lincoln, U.K. Her research interests include intelligent systems and machine fault detection and diagnosis.

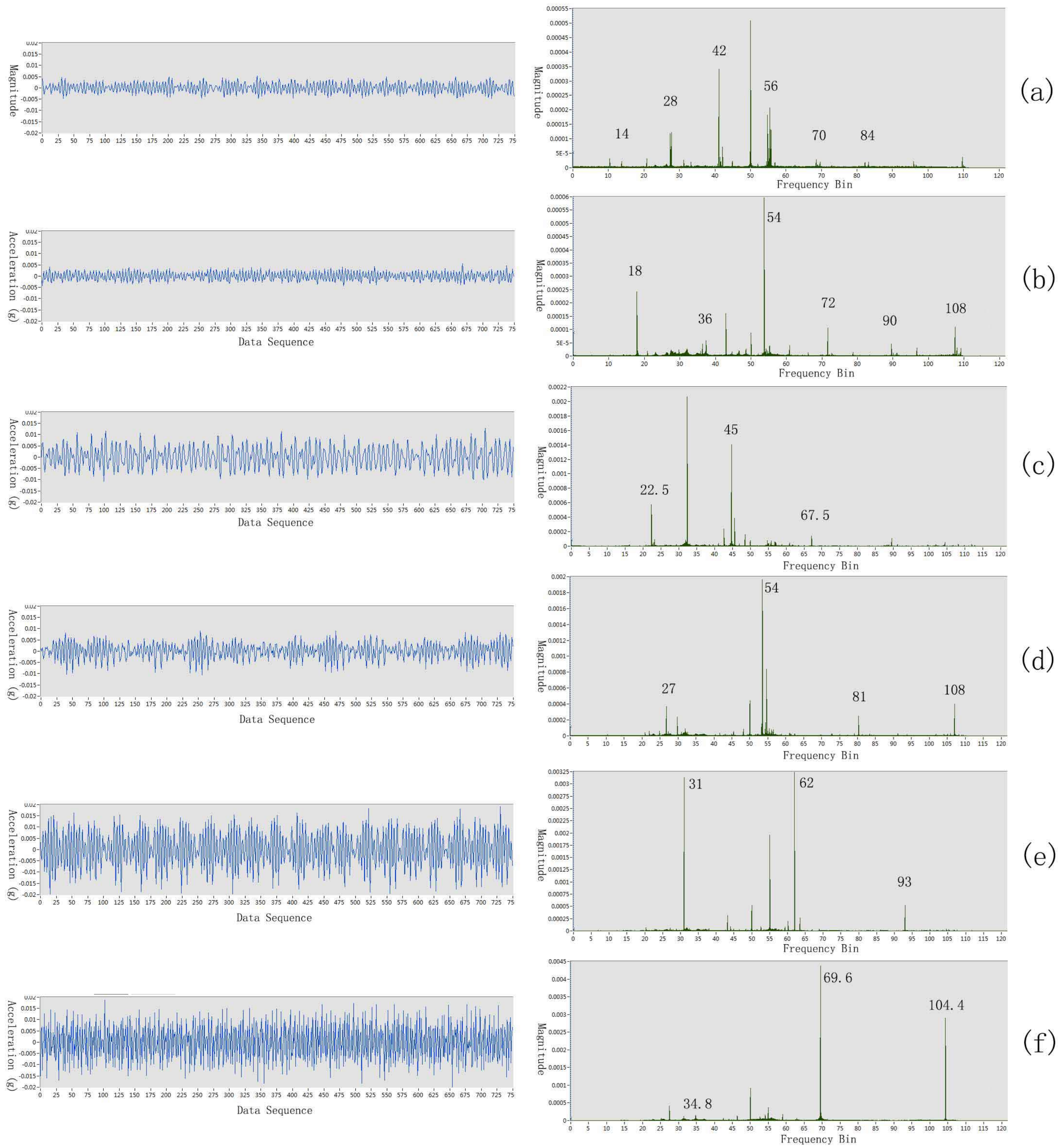



Fig. 7: Signal and spectrum at different flow rate when 6 pipelines clogging:(a) 0.6L/S, (b) 0.8L/S, (c) 1.0L/S, (d) 1.2L/S, (e) 1.4L/S, (f) 1.6L/S.